# SPACE STATION PROPULSION TECHNOLOGY

SECOND ANNUAL PROGRESS REPORT

24 MAY 1986 - 02 OCTOBER 1987

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

CONTRACT NAS8-36418
8 OCTOBER 1987

PREPARED BY:

PROPULSION PROGRAMS
ROCKETDYNE DIVISION

A. M. NORMAN
PROJECT ENGINEER
SPACE STATION PROPULSION

G. L. BRILEY
PROJECT MANAGER
SPACE STATION PROPULSION

S. A. EVANS
PROGRAM MANAGER
SPACE STATION PROPULSION

ROCKWELL INTERNATIONAL CORPORATION
6633 CANOGA AVENUE
CANOGA PARK, CA 91304

20242g-1g-3790

(NASA-CR-179260) SPACE STATION PROPULSION TECHNOLOGY Annual Progress Report No. 2, 24 May 1986 - 2 Oct. 1987 (Rockwell International Corp.) 34 p CSCL 21H

N88-15835

Unclas
G3/20 0120671

CONTENTS


| | Page |
|---|---|
| Introduction | 1 |
| Data Evaluation | 4 |
| Work in Progress | 32 |
| Funding | 32 |


FIGURES


1. Test Bed Accumulator Module .......... 3
2. Thruster, Resistojet, and Accumulator Module Schematic .......... 8
3. Oxidizer System Blowdown Data ($GN_2$ Used in Place of GOX) .......... 10
4. Fuel System Blowdown Data (GHe Used in Place of $GH_2$) .......... 11
5. Comparison of Tank Pressures From Blowdown Versus Theoretical 80% Isothermal .......... 12
6. Oxidizer Accumulator Pressure During Acceptance Test .......... 13
7. Fuel Accumulator Pressure During Acceptance Test .......... 14
8. Oxidizer Accumulator Outlet Temperature During Acceptance Test .......... 15
9. Oxidizer Accumulator Skin Temperature During Acceptance Test .......... 16
10. Fuel Accumulator Outlet Temperature During Acceptance Test .......... 17
11. Fuel Accumulator Skin Temperature During Acceptance Test .......... 18
12. Rocketdyne Prototype 8:1 Thruster .......... 20
13. Rocketdyne Prototype Thruster in Test Bed for Initial Testing .......... 21
14. Thrust Measuring System Before Installation in Test Bed .......... 22
15. Rocketdyne Prototype Thruster in Thrust Measuring System for Checkout of System on Test Bed .......... 23
16. Water Electrolysis Module in MSFC Workshop .......... 25
17. LSI Technician Connecting Electrolysis Unit to Pressure Container Pass Throughs .......... 26
18. Installation of Water Electrolysis Module into Stand .......... 27
19. Water Electrolysis Module Installed on Top of Accumulator Module in Stand .......... 28

## TABLES


| | | Page |
|---|---|---|
| 1. | Space Station Propulsion Tests | 5 |
| 2. | Initial Acceptance Test Sequence | 9 |
| 3. | Electrolysis Test Plant (Three Primary Test Series are Planned on Electrolysis Systems) | 29 |
| 4. | Summary of Dryer Saturation Performance as a Function of Product Gas Water Vapor Flow Rate | 30 |

## Introduction

This annual Progress Report for the period 24 May 1986 through 02 October 1987 describes the progress of the Space Station Propulsion Technology Program, NAS8-36418.

The objectives of this program are to provide a demonstration of hydrogen/oxygen propulsion technology readiness for the IOC space station application, specifically gaseous hydrogen/oxygen and warn hydrogen thruster concepts, and to establish a means for evolving from the IOC space station propulsion system (SSPS) to that required to support and interface with advanced station functions. These objectives were met by analytical studies and by furnishing a propulsion test bed to MSFC for testing.

The program was organized in six tasks. In Task I, candidate IOC SSPS concept definition, a range of design concepts for the IOC SSPS were synthesized and evaluated. The most attractive candidates were carried into a more detailed conceptual design. In Task II, SSPS test bed design and fabrication, the propulsion test bed was designed, fabricated, and delivered to MSFC with associated test plans and documentation. A contract change to modify an existing $O_2/H_2$ thruster for test bed operation at a mixture ratio of 8 was added to this effort. In Task III, advanced SSPS concept definition, evolutionary growth concepts were to be synthesized and evaluated. In Tasks IV, V, and VI, Rocketdyne was to provide ongoing support to the test program carried out by MSFC and conduct configuration updates as needed to demonstrate evolutionary growth concepts.

The program was initiated on 24 May 1985 and proceeded on the original plan until January 1986. At that time, decisions being made on the Phase B Space Station program caused a change in emphasis and a funding hiatus. By January 1986, the accumulator module and microprocessor controller had been delivered to MSFC and preparation for fabricating the supercritical storage module was underway. A revised study plan was submitted in June 1986.

The revised plan addressed the change in direction from using supercritical propellant storage at IOC to subcritical storage and water electrolysis. The revised plan redirected remaining fabrication and test support tasks toward the water electrolysis approach. Specifically, refurbishment to a subcritical configuration was replaced with preparation, checkout, and integration of components needed to demonstrate water electrolysis, main thrusters, condition monitoring, and use of waste gases with resistojets. As flight-type components become available, they will be installed and tested on the test bed.

The baseline propulsion technologies being considered are gaseous oxygen/hydrogen and resistively heated waste gas concepts. The study plan encompasses both near-term and future plans for SSPS technology demonstration. Three phases are included in the test bed program:

- Phase I--Demonstrating an accumulator system and microprocessor controller using oxygen/hydrogen thrusters for IOC space station propulsion

- Phase II--Demonstrating electrolysis generation of oxygen/hydrogen propellants

- Phase III--Incorporating waste gas disposal system, condition monitoring, and flight-type components.

During August 1986, the design and fabrication of a thrust measurement system was added to the effort.

During the summer and early fall of 1986, the installation and activation of the test bed and its control system progressed steadily. The test bed consists of propellant accumulators, valving, instrumentation, and controls configured in a 9-foot cube structure (Fig. 1) designed to fit into the MSFC altitude chamber at Test Stand 300 while simulating a basic building block structural element of the space station. This configuration permits mounting of various types of supply modules on top of the basic accumulator module.

ORIGINAL PAGE IS
OF POOR QUALITY

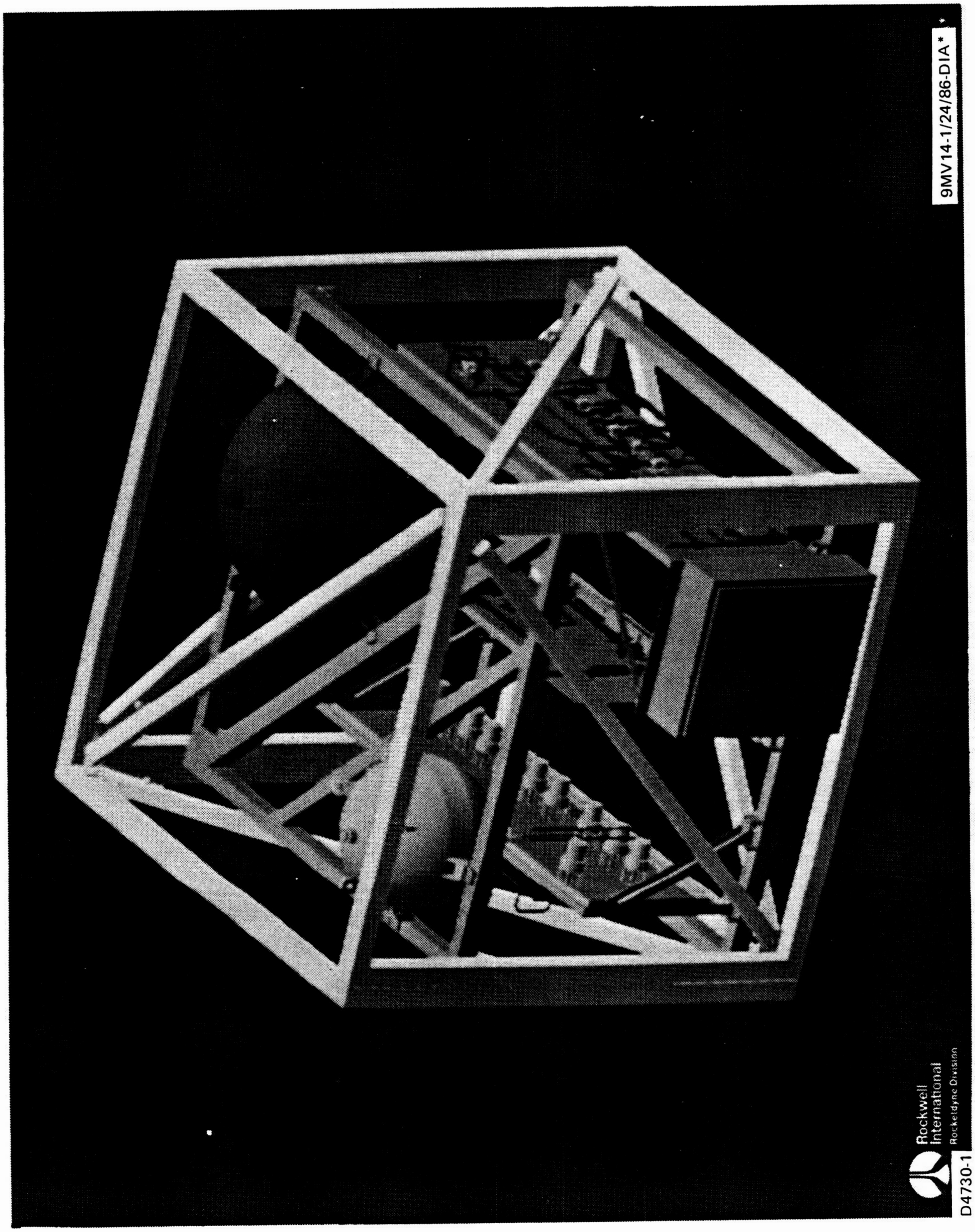



Figure 1. Test Bed Accumulator Module

The control system is a microprocessor-based system which can control the entire test sequence autonomously. Sixty-four end devices can be controlled and monitored and 48 transducer data channels can be monitored for use as red-lines or "go-nogo" checks. A remote terminal located at the Rocketdyne Canoga Park, California facility was connected to the system via modems so that the system software can be modified and checked whenever required. The system displays 24 channels of reduced data updated on a one-second time basis, and this data can also be displayed on the remote terminal during test operations.

The control system was tested in several ways to verify satisfactory operation. The system software and hardware were verified by running a checkout test program which cycled all the system software commands and input/output channels.

The transducer channels were all verified by comparing the resultant data to that from similarly located channels on the area data acquisition system. The final acceptance of the system was based on successfully operating the test bed automatically when the acceptance test blowdowns were made.

The acceptance test blowdowns were conducted in October and early November. The sequence was designed to simulate thruster and resistojet firing by bleeding the gas through dump valves. Since the original design was for a 4:1 mixture ratio thruster, the acceptance tests were performed at those conditions.

## Data Evaluation

A total of 65 preacceptance, acceptance, and system evaluation tests have been conducted on the space station propulsion test bed. Table 1 is a summary of all tests to date. As can be seen in the table, several tests were unsuccessful due to no ignition. This has been traced to a faulty spark cable and a marginal new exciter. Both have been replaced, and the ignition problem has been resolved.

Table 1. Space Station Propulsion Tests
(Sheet 1 of 2)

| Test Number | Date | Test Type | Target Mixrat | Target PC (psia) | Target Time (sec) | Actual Time (sec) | Test Results | Thruster | Spark Exciter | Ign Seq | Hardware Configuration | Information | Pulse Time | Pulse Cycles |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 103-001 | 10/03/86 | TB B/D | N/A | N/A | 550 | 550 | Good | N/A | N/A | A | Initial Checkout | | | |
| 103-002 | 10/15/86 | TB B/D | N/A | N/A | 500 | 500 | Good | N/A | N/A | A | Checkout | | | |
| 103-003 | 10/28/86 | TB B/D | N/A | N/A | Max | 611 | Good | N/A | N/A | A | Acceptance Test | | | |
| 103-004 | 12/03/86 | TH B/D | N/A | N/A | 15 | 0 | No good | IR&D | J2 | A | | R/L Cut | | |
| 103-005 | 12/03/86 | TH B/D | N/A | N/A | 15 | 15 | Good | IR&D | J2 | A | | Duration | | |
| 103-006 | 12/03/86 | Thrust | 8.0 | 100 | 1 | 1 | Ign | IR&D | J2 | A | | No info | | |
| 103-007 | 12/03/86 | Thrust | 8.0 | 100 | 5 | 5 | Ign | IR&D | J2 | A | | No info | | |
| 103-008 | 12/04/86 | Thrust | 8.0 | 100 | Max | 291 | Ign | IR&D | J2 | A | | Seal leaked, cut | | |
| 103-009 | 12/09/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | | 0.06 | 0 |
| 103-010 | 12/09/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | | 1.00 | 0 |
| 103-011 | 12/09/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | Low voltage | 0.06 | 0 |
| 103-012 | 12/10/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | Normal voltage | 0.06 | 0 |
| 103-013 | 12/10/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | Normal voltage | 0.08 | 0 |
| 103-014 | 12/10/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | Normal voltage | 1.00 | 0 |
| 103-015 | 12/11/86 | Thrust | 8.0 | 100 | Pulse | Pulse | No ign | IR&D | J2 | A | | BD failed | 1.00 | 0 |
| 103-016 | 03/11/87 | TH B/D | N/A | N/A | | | No good | IR&D | J2 | A | | SEQ cut | | |
| 103-017 | 03/12/87 | TH B/D | N/A | N/A | | | Good | IR&D | J2 | A | | | | |
| 103-018 | 03/12/87 | Thrust | 8.0 | 100 | 1 | 1 | Ign | IR&D | J2 | A | | H2 man in Fl | | |
| 103-019 | 03/12/87 | Thrust | 8.0 | 100 | 5 | | Ign | IR&D | J2 | A | | H2 man in Fl | | |
| 103-020 | 03/13/87 | Thrust | 8.0 | 100 | 250 | 0 | No ign | IR&D | J2 | A | | BD failed | | |
| 103-021 | 03/16/87 | Thrust | 8.0 | 100 | 250 | 60 | Ign | IR&D | J2 | A | | R/L cut | | |
| 103-022 | 03/17/87 | Thrust | 8.0 | 50 | 5 | 5 | Ign | IR&D | J2 | A | | H2 man in Fl | | |
| 103-023 | 03/17/87 | Thrust | 8.0 | 50 | 5 | 5 | Ign | IR&D | J2 | A | | H2 man in Fl | | |
| 103-024 | 03/17/87 | Thrust | 8.0 | 50 | 20 | 20 | Ign | IR&D | J2 | A | | H2 man in Fl | | |
| 103-025 | 07/20/87 | Thrust | 8.0 | 100 | 10 | 10 | Ign | IR&D | J2 | A | | C/O test | | |
| 103-026 | 07/20/87 | Thrust | 8.0 | 100 | 100 | 25 | Ign | IR&D | J2 | A | | C/O test, manual cut? | | |
| 103-027 | 07/20/87 | TH B/D | N/A | N/A | | | B/D | IR&D | J2 | A | | R/L cut | | |
| 103-028 | 07/31/87 | Elec | N/A | N/A | | 244800 | Incompl | IR&D | J2 | A | | Electrolysis test | | |
| 103-029 | 08/13/87 | TH B/D | N/A | N/A | | | Good | IR&D | J2 | A | | | | |
| 103-030 | 08/13/87 | Thrust | 6.0 | 100 | 120 | | Ign | IR&D | J2 | A | | | | |
| 103-031 | 08/13/87 | Thrust | 8.0 | 100 | 120 | 0 | No ign | IR&D | J2 | A | | | | |
| 103-032 | 08/13/87 | Thrust | 8.0 | 100 | 120 | 0 | No ign | IR&D | J2 | A | | | | |
| 103-033 | 08/14/87 | Thrust | 8.0 | 100 | 120 | 0 | No ign | IR&D | J2 | A | | | | |
| 103-034 | 08/14/87 | Thrust | 6.0 | 100 | 120 | 0 | No ign | IR&D | J2 | A | | H2 vlv fail | | |
| 103-035 | 08/14/87 | Thrust | 7.0 | 100 | 120 | 0 | No ign | IR&D | J2 | A | | SP cable at vac. suspect | | |
| 103-036 | 08/19/87 | Thrust | 7.0 | 100 | 120 | 120 | Ign | IR&D | J2 | A | | Tubing added to cable | | |
| 103-037 | 08/19/87 | Thrust | 7.5 | 100 | 120 | 120 | Ign | IR&D | J2 | A | | Tubing added | | |
| 103-038 | 08/19/87 | Thrust | 8.0 | 100 | 120 | 120 | Ign | IR&D | J2 | A | | Tubing added | | |

Note:

Ignition sequence A is spark 20 msec after $O_2$ valve is signaled to open. Ignition sequence B is spark 100 msec before $O_2$ valve is signaled to open.

0251e/rmr

Table 1. Space Station Propulsion Tests
(Sheet 2 of 2)

| Test Number | Date | Test Type | Target Mixrat | Target PC (psia) | Target Time (sec) | Actual Time (sec) | Test Results | Thruster | Spark Exciter | Ign Seq | Hardware Configuration | Information | Pulse Time | Pulse Cycles |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 103-039 | 08/20/87 | Thrust | 8.0 | 100 | 120 | 23 | Ign | IR&D | J2 | A | | R/L cut | | |
| 103-040 | 08/20/87 | Thrust | 8.0 | 100 | 120 | 3 | Ign | IR&D | J2 | A | | R/L cut | | |
| 103-041 | 08/26/87 | Thrust | 8.0 | 100 | 120 | 120 | Ign | IR&D | J2 | A | | Replaced instrument | | |
| 103-042 | 08/26/87 | Thrust | 8.0 | 100 | 120 | 113 | Ign | IR&D | J2 | A | | Cut | | |
| 103-043 | 09/01/87 | TH B/D | N/A | N/A | | | B/D | LeRC#1 | Simmonds#1 | A | New thruster & exciter | | | |
| 103-044 | 09/01/87 | TH B/D | N/A | N/A | | | Good? | LeRC#1 | Simmonds#1 | A | | | | |
| 103-045 | 09/01/87 | TH B/D | N/A | N/A | | | B/D | LeRC#1 | Simmonds#1 | A | | | | |
| 103-046 | 09/01/87 | Thrust | 8.0 | 100 | 1 | 1 | Ign | LeRC#1 | Simmonds#1 | A | | | | |
| 103-047 | 09/02/87 | Thrust | 8.0 | 100 | 10 | 0 | No ign | LeRC#1 | Simmonds#1 | A | | | | |
| 103-048 | 09/02/87 | Thrust | 8.0 | 100 | 10 | 0 | No ign | LeRC#1 | Simmonds#1 | A | | | | |
| 103-049 | 09/02/87 | Thrust | 8.0 | 100 | 10 | 0 | No ign | LeRC#1 | Simmonds#1 | A | | No spark | | |
| 103-050 | 09/11/87 | Thrust | 8.0 | 100 | 10 | 0 | No ign | LeRC#1 | Simmonds#3 | A | New exciter & cable | Tubing added to cable | | |
| 103-051 | 09/11/87 | Thrust | 8.0 | 100 | 10 | 0 | No ign | LeRC#1 | Simmonds#3 | A | No change from 50 | | | |
| 103-052 | 09/15/87 | Thrust | 8.0 | 100 | 5 | 5 | Ign | LeRC#1 | Simmonds#3 | A | No change from 50 | Mirror, prg on cable | | |
| 103-053 | 09/15/87 | Thrust | 8.0 | 100 | 2 | 0 | No ign | LeRC#1 | Simmonds#3 | A | No change from 50 | Mirror, prg on cable | | |
| 103-054 | 09/15/87 | Thrust | 8.0 | 100 | 2 | 2 | Ign | LeRC#1 | Simmonds#3 | B | No change from 50 | Mirror, prg cable, new seq | | |
| 103-055 | 09/15/87 | Thrust | 8.0 | 100 | 2 | 0 | No ign | LeRC#1 | Simmonds#3 | B | No change from 50 | See 054, also H2 vlv fail | | |
| 103-056 | 09/17/87 | Thrust | 8.0 | 100 | 10 | 0 | No ign | LeRC#1 | Simmonds#3 | A | Fuel vlv S/N 015 install | Old seq, no mirror | | |
| 103-057 | 09/17/87 | Thrust | 8.0 | 100 | 10 | 10 | Ign | LeRC#1 | Simmonds#3 | B | No change from 56 | New seq but late ign | | |
| 103-058 | 09/17/87 | Thrust | 8.0 | 100 | 30 | 0 | No ign | LeRC#1 | Simmonds#3 | B | No change from 56 | | | |
| 103-059 | 09/17/87 | Thrust | 8.0 | 100 | 30 | 0 | No ign | LeRC#1 | Simmonds#3 | B | No change from 56 | DG timing blip | | |
| 103-060 | 09/29/87 | Thrust | 8.0 | 100 | 30 | 0 | No ign | LeRC#1 | Simmonds#2 | B | New exciter & cable | | | |
| 103-061 | 09/29/87 | Thrust | 8.0 | 100 | 30 | 0 | No ign | LeRC#1 | Simmonds#2 | B | No change from 60 | | | |
| 103-062 | 09/29/87 | Thrust | 8.0 | 100 | 30 | 0 | No ign | LeRC#1 | Simmonds#2 | B | No change from 60 | | | |
| 103-063 | 09/30/87 | Thrust | 8.0 | 100 | Min | 0 | No ign | LeRC#1 | Simmonds#2 | B | No change from 60 | At atmos pres | | |
| 103-064 | 09/30/87 | El B/D | N/A | N/A | N/A | N/A | Good | N/A | N/A | | | Dryer blowdown | | |
| 103-065 | 10/01/87 | Thrust | 8.0 | 100 | Min | 0 | No ign | IR&D | Simmonds#2 | B | Changed thruster | At atmos pres, with mir | | |

Note:

Ignition sequence A is spark 20 msec after $O_2$ valve is signaled to open. Ignition sequence B is spark 100 msec before $O_2$ valve is signaled to open.

0251e/rmr

The schematic giving the system layout is given in Fig. 2. Redundant instrumentation systems were provided for the data recording function and the control function.

As previously described, the propulsion test bed is configured to support both a resistojet (electrically heated waste gas) and a bipropellant hydrogen/oxygen thruster.

Initial checkout and acceptance testing involved the system evaluation of both the resistojet and $GO_2/GH_2$ thruster systems.

The test sequence employed is detailed in Table 2. The sequence description is initiated after the $H_2$ and $O_2$ accumulators have been charged from a facility supply.

The initial acceptance test (P103-2) was conducted using $GN_2$ to simulate $O_2$ and GHe to simulate $H_2$. The test was conducted using the sequence of Table 1. Representative typical data from this test are given in Fig. 3 and 4. Fig. 3 shows the accumulator pressure and temperature and the venturi and thruster inlet pressures for the oxidizer system. The same data is given in Fig. 4 for the $H_2$ system. The test was terminated when the oxidizer tank decayed to 300 psia.

A comparison between the measured and calculated tank pressures are given in Fig. 5. The calculated values were based on an 80% isothermal condition.

Data typical of the test where $GO_2$ and $GH_2$ were used as the test fluids were obtained on the final acceptance test. These data are presented in Fig. 6 through 11. Figure 6 shows the $GO_2$ accumulator pressure. Fig. 7 gives the same pressure data for the $GH_2$ system. Temperature data are given in Fig. 8 and 9 for the oxidizer system and Fig. 10 and 11 for the hydrogen system. The oxidizer system characteristics are the same for both the $N_2$ and $O_2$ use fluids as expected. However, the $H_2$ and He tests exhibit different thermal characteristics. This was also expected and the observed thermal and hydraulic differences are predictable.

ORIGINAL PAGE IS
OF POOR QUALITY

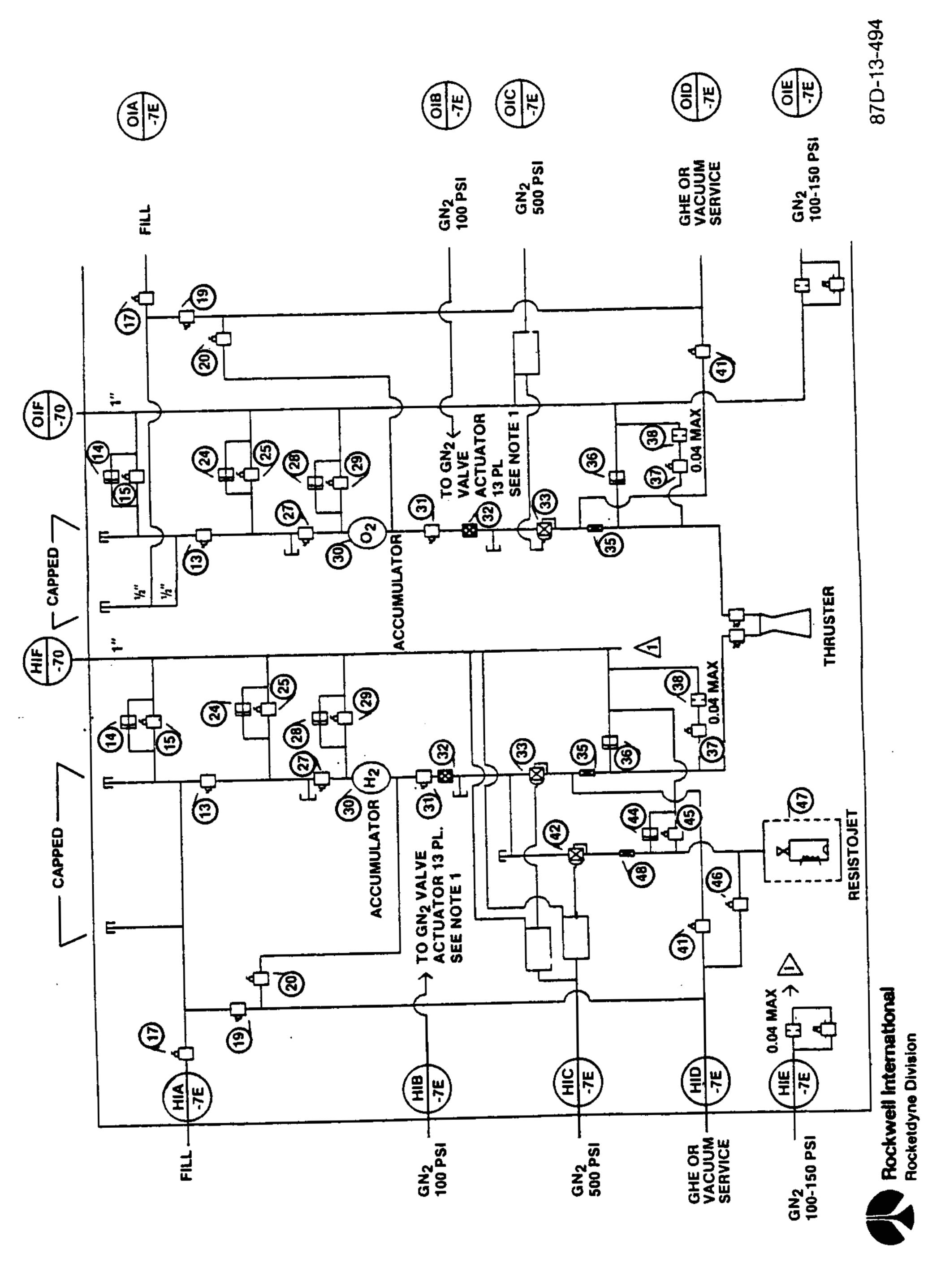



Figure 2. Thruster, Resistojet, and Accumulator Module Schematic

Table 2. Initial Acceptance Test Sequence

| Time, sec (Relative) | Event | Valve Identification (Fig. 2) |
| --- | --- | --- |
| 0.25 | $H_2$ and $O_2$ accumulator outlet valves open | 31 |
| 1.20 | Initiate $H_2$ line pressurization | 33 |
| 15.80 | $H_2$ line pressurization complete | 33 |
| 15.88 | Initiate $O_2$ line pressurization | 33 |
| 29.18 | $O_2$ line pressurization complete | 33 |
| 29.26 | Initiate resistojet line pressurization | 42 |
| 42.82 | Resistojet line pressurization complete | 42 |
| 71.16 | Initiate resistojet firing | C |
| 121.18 | Complete resistojet firing | C |
| 126.16 | Initiate thruster firing | A&B |
| 688.02 | Complete thruster firing | A&B |
| 688.02 | Initiate test bed safing | -- |
| 728.00 | Facility test bed safing | -- |

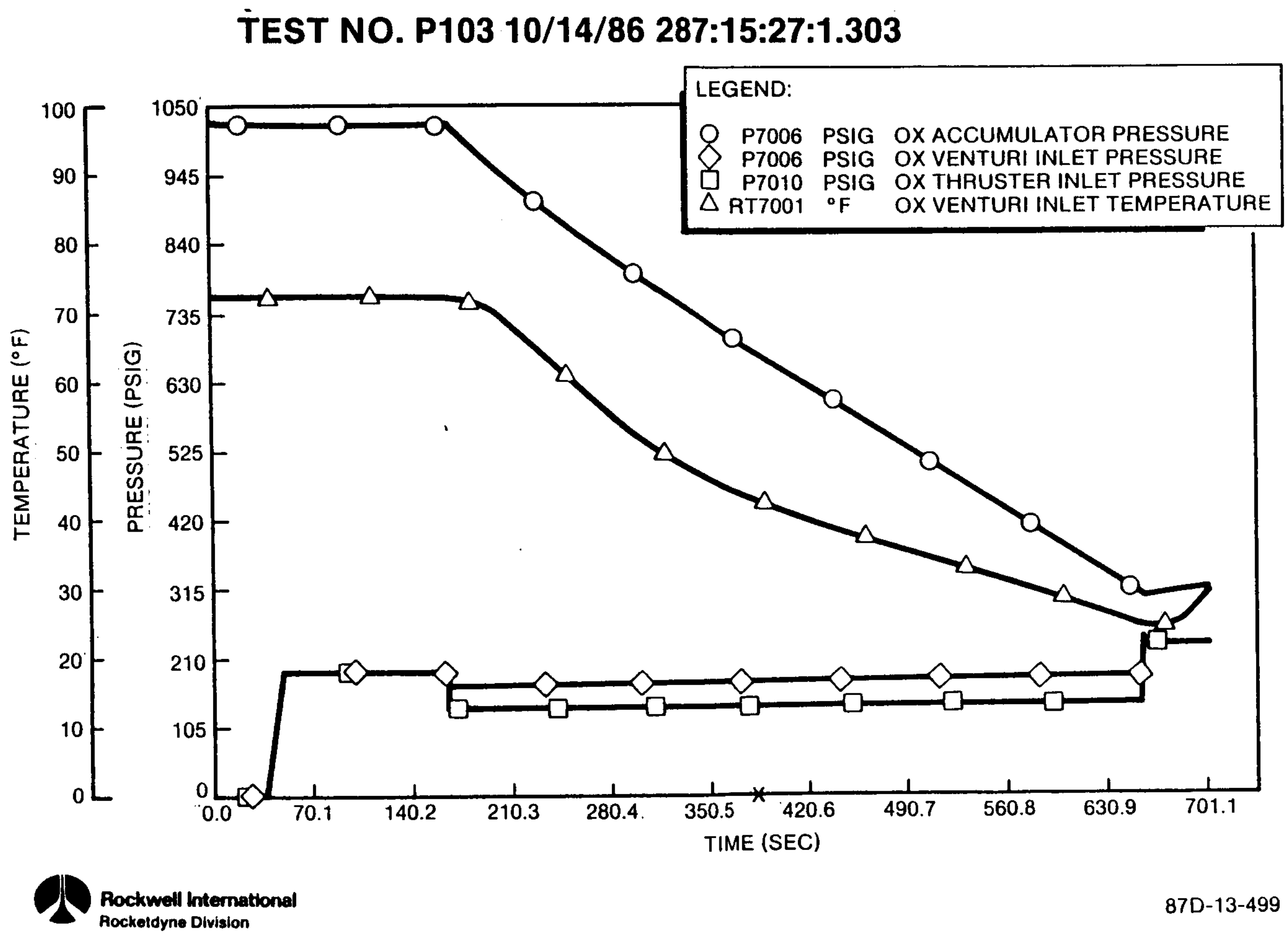



Figure 3. Oxidizer System Blowdown Data ($GN_2$ Used in Place of GOX)

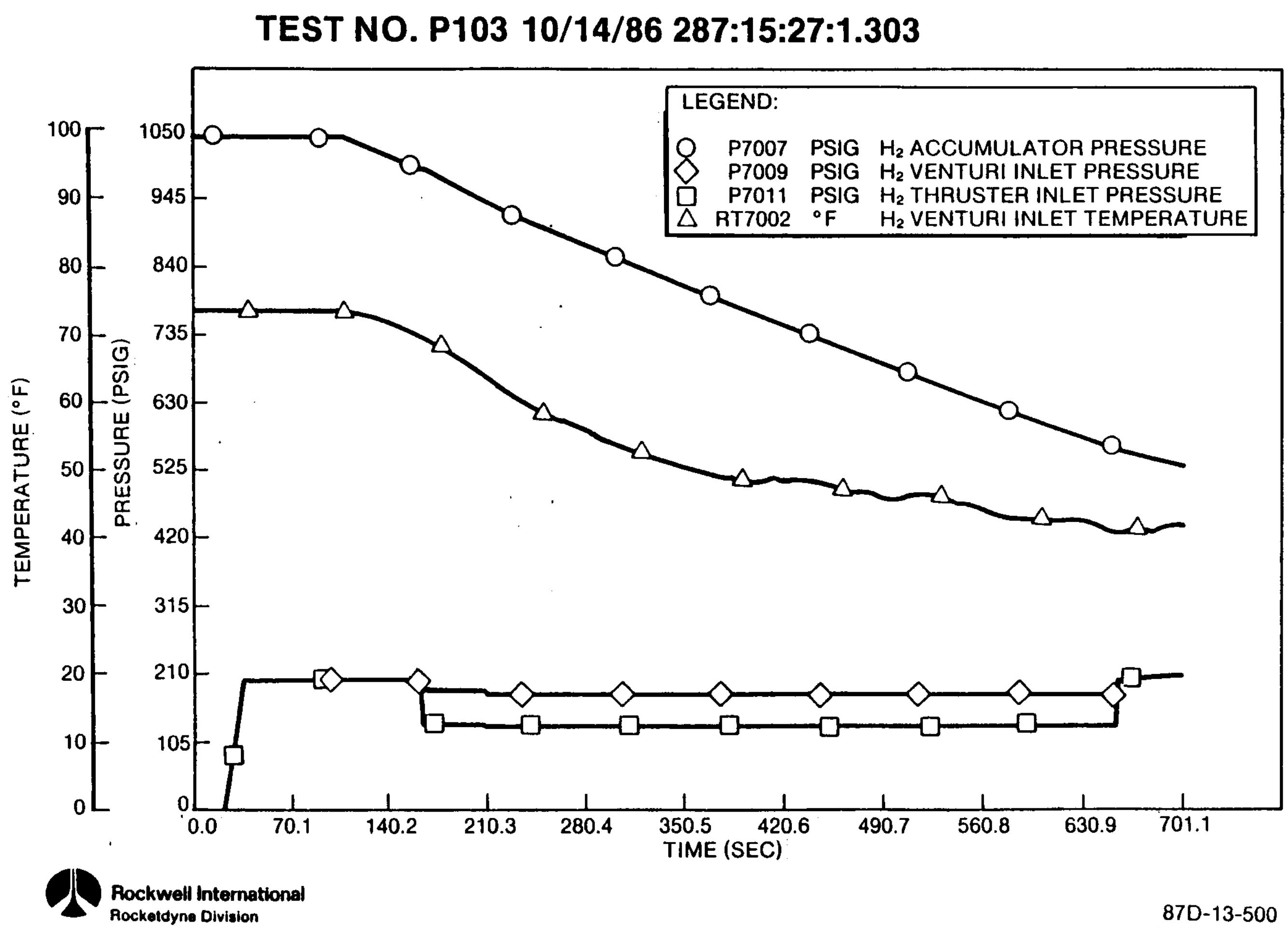
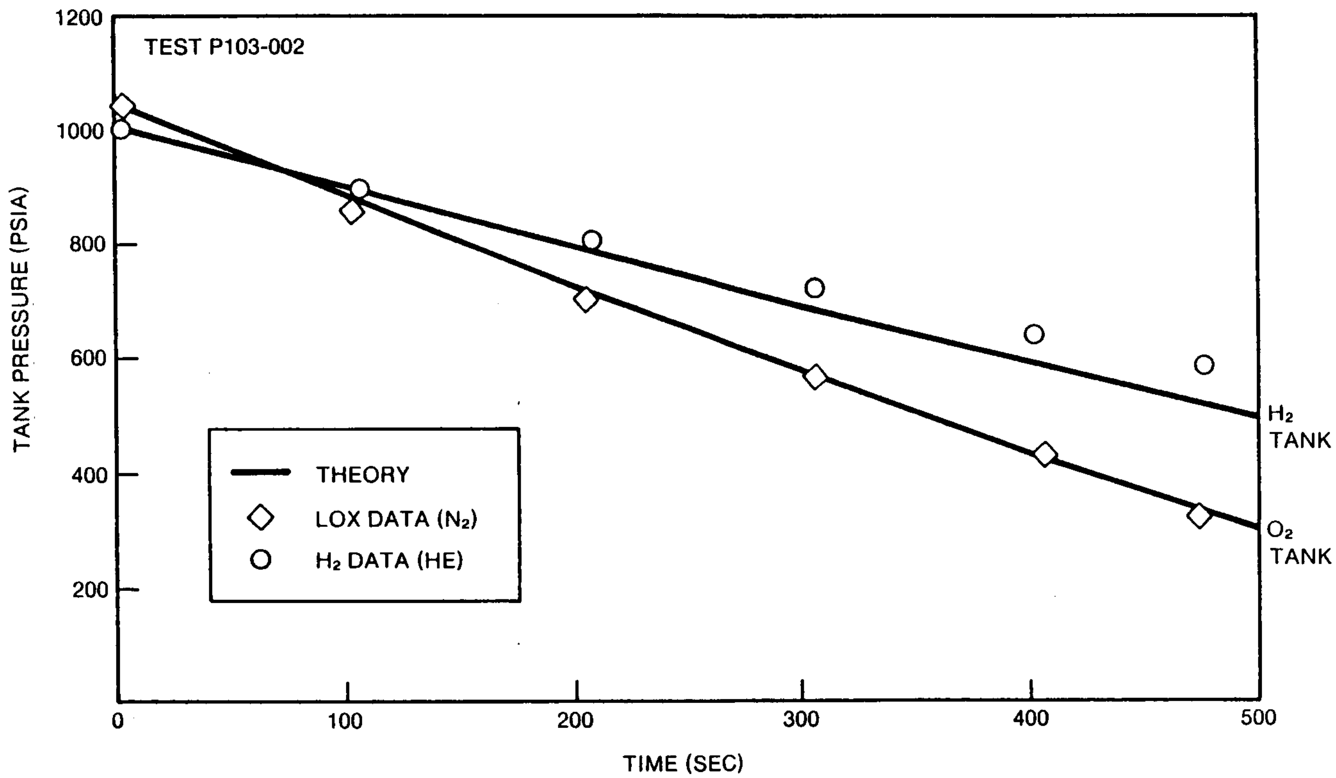


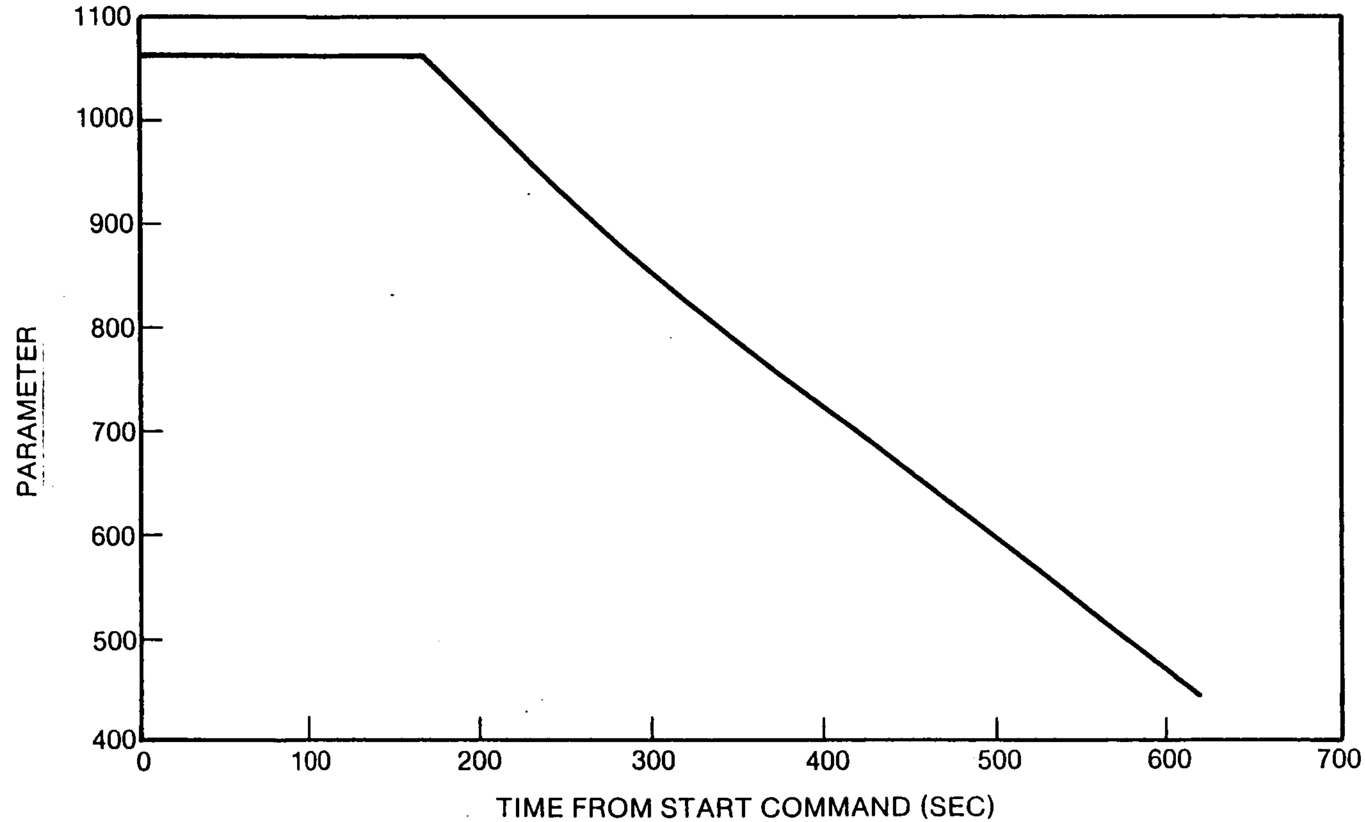

Figure 4. Fuel System Blowdown Data
(GHe Used in Place of $GH_2$)




Rockwell International
Rocketdyne Division

87D-13-501

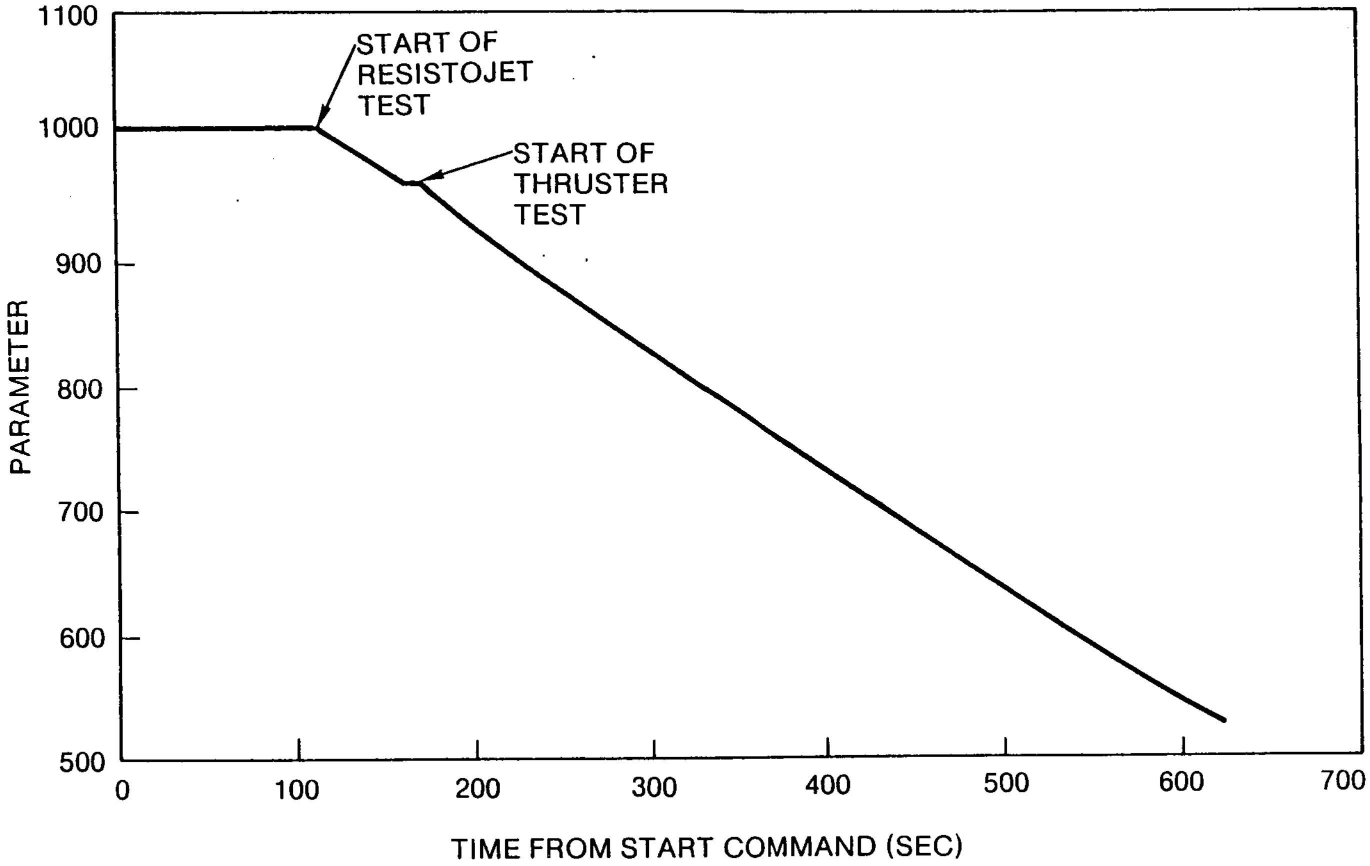
Figure 5. Comparison of Tank Pressures From Blowdown Versus Theoretical 80% Isothermal




Rockwell International
Rocketdyne Division

87D-13-502

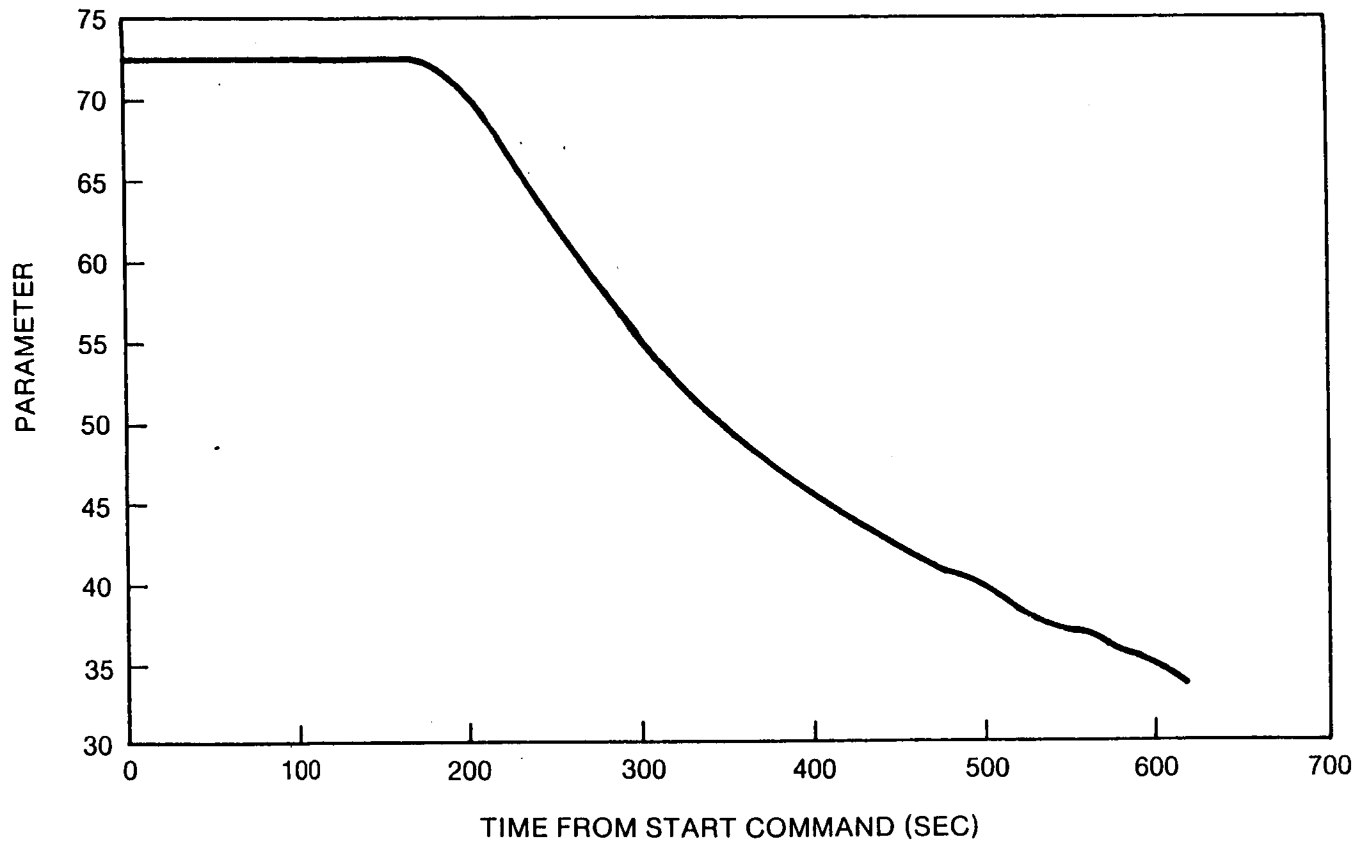
Figure 6. Oxidizer Accumulator Pressure
During Acceptance Test




87D-13-50?

Rockwell International
Rocketdyne Division

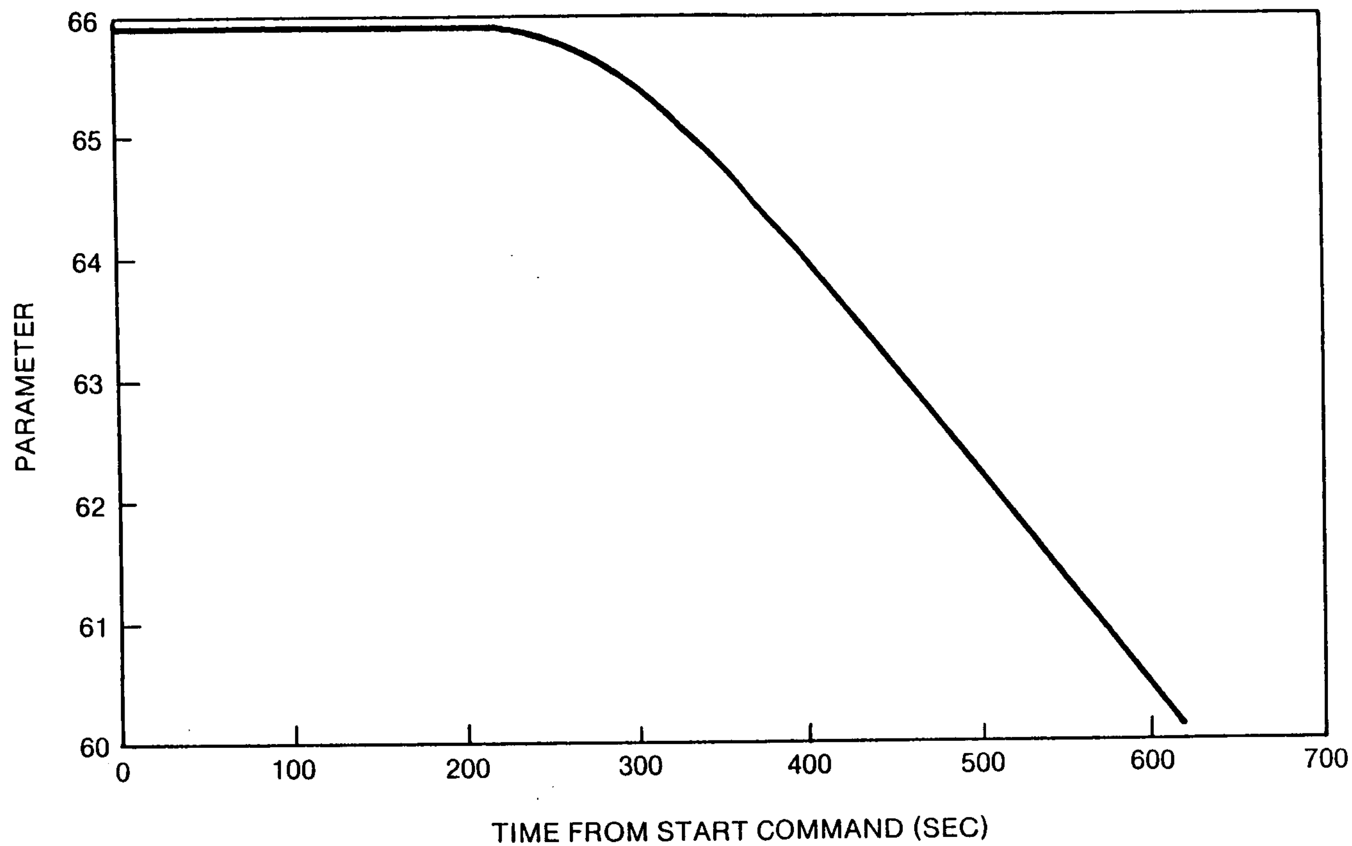
Figure 7. Fuel Accumulator Pressure During Acceptance Test




Rockwell International
Rocketdyne Division

87D-13-504

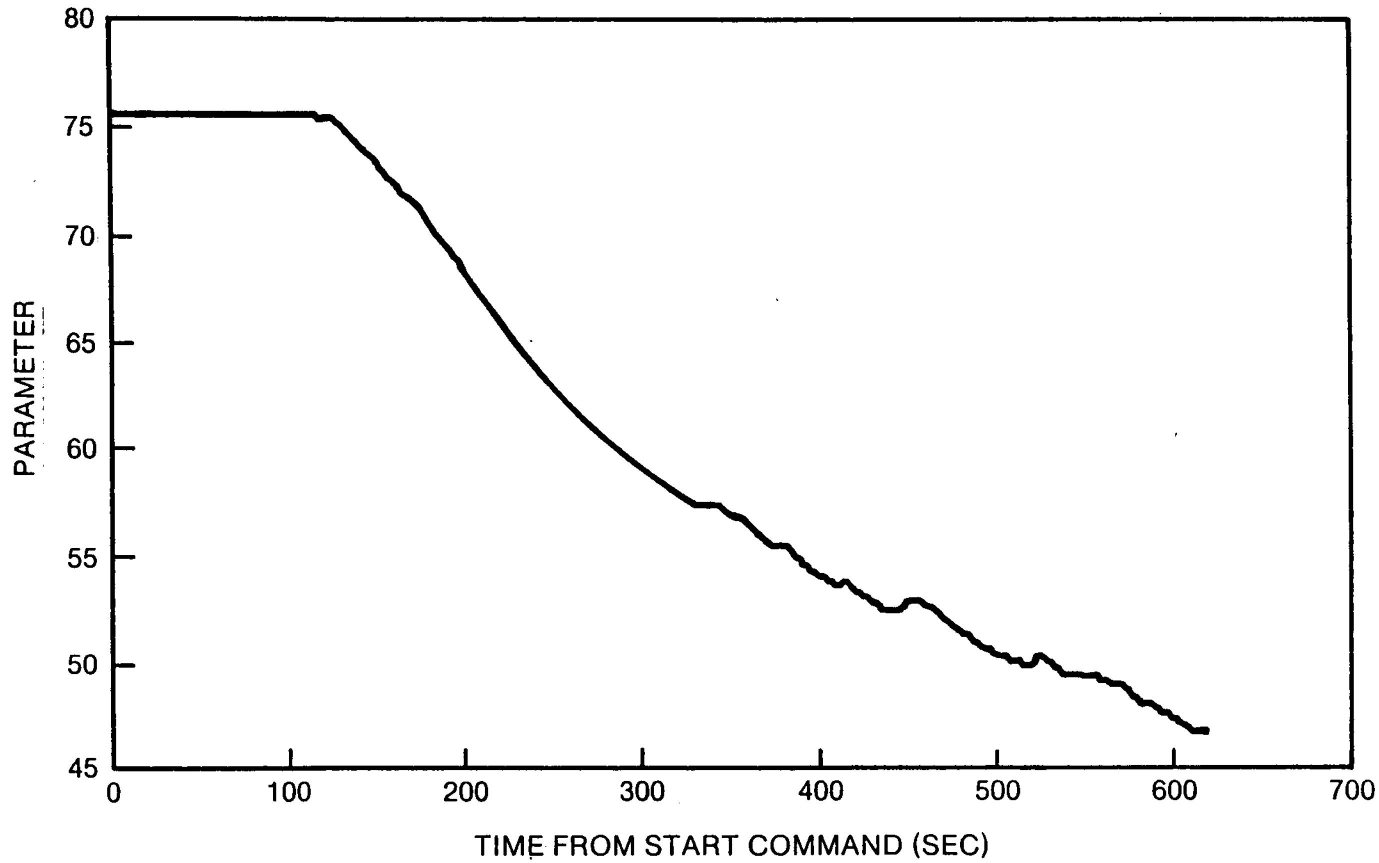
Figure 8. Oxidizer Accumulator Outlet Temperature During Acceptance Test




Rockwell International
Rocketdyne Division

87D-13-505

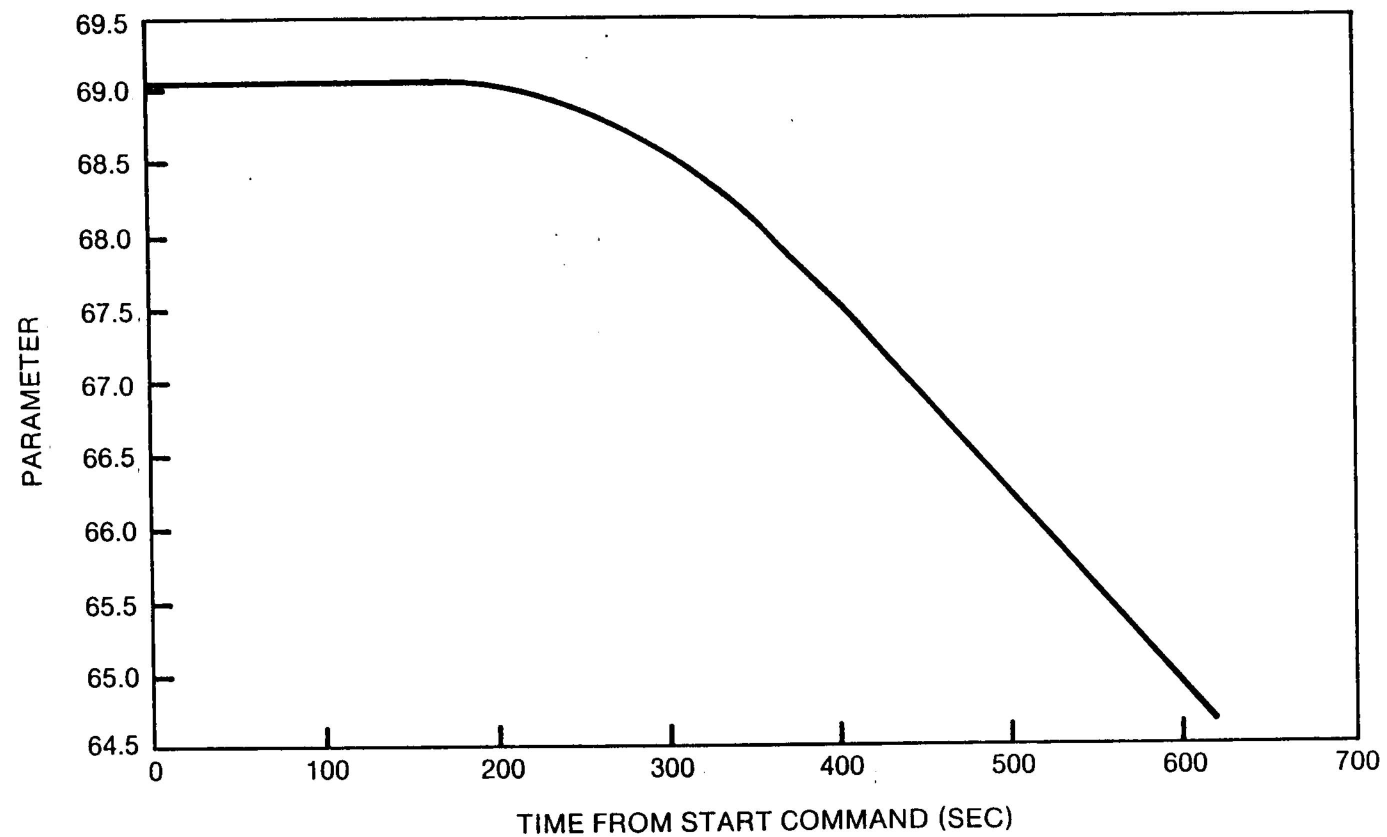
Figure 9. Oxidizer Accumulator Skin Temperature During Acceptance Test




Rockwell International
Rocketdyne Division

87D-13-506

Figure 10. Fuel Accumulator Outlet Temperature During Acceptance Test




Rockwell International
Rocketdyne Division

87D-13-507

Figure 11. Fuel Accumulator Skin Temperature During Acceptance Test

Following the acceptance test completion, the Rocketdyne 25-lbf prototype thruster (Fig. 12) was installed in the test bed. To turn the exhaust gas away from the cell floor, a facility water-cooled exhaust duct was placed beneath the engine shown in Fig. 13. Minor modifications were made to the test bed plumbing to run the thruster at the new design point of 8:1 mixture ratio.

A series of tests were conducted on the system in December 1986, culminating with the thruster firing for 291 seconds, the oxygen tank maximum duration at these conditions.

A thrust measuring system (Fig. 14) for use on the test bed was added to the contract. This was designed and fabricated at Rocketdyne for either horizontal or vertical use and can be calibrated remotely at vacuum conditions with run lines pressurized to remove all external load effects.

The thrust system was installed in February 1987, and the first thruster firings to obtain data from it were performed in March. Fig. 15 shows the thruster mounted with thrust system on the test bed. Initial data results indicated a discrepancy of about 3 pounds between the calculated and measured values. A series of calibration checks were made which revealed that the mount on the stand was flexing, thereby allowing the entire thrust system to move. Additional braces were added, and the movement was reduced to acceptably low levels. The thrust calibration and measuring systems were shown to be working within 0.1%, and the data is now expected to be within 1% including the residual movement.

To demonstrate the totally automated capability of the system, one of the firings during the thrust measuring system series was performed from California. After setup was completed, control of the system was switched to the Rocketdyne remote terminal and a 5-second thruster firing was satisfactorily conducted from 2000 miles distance.

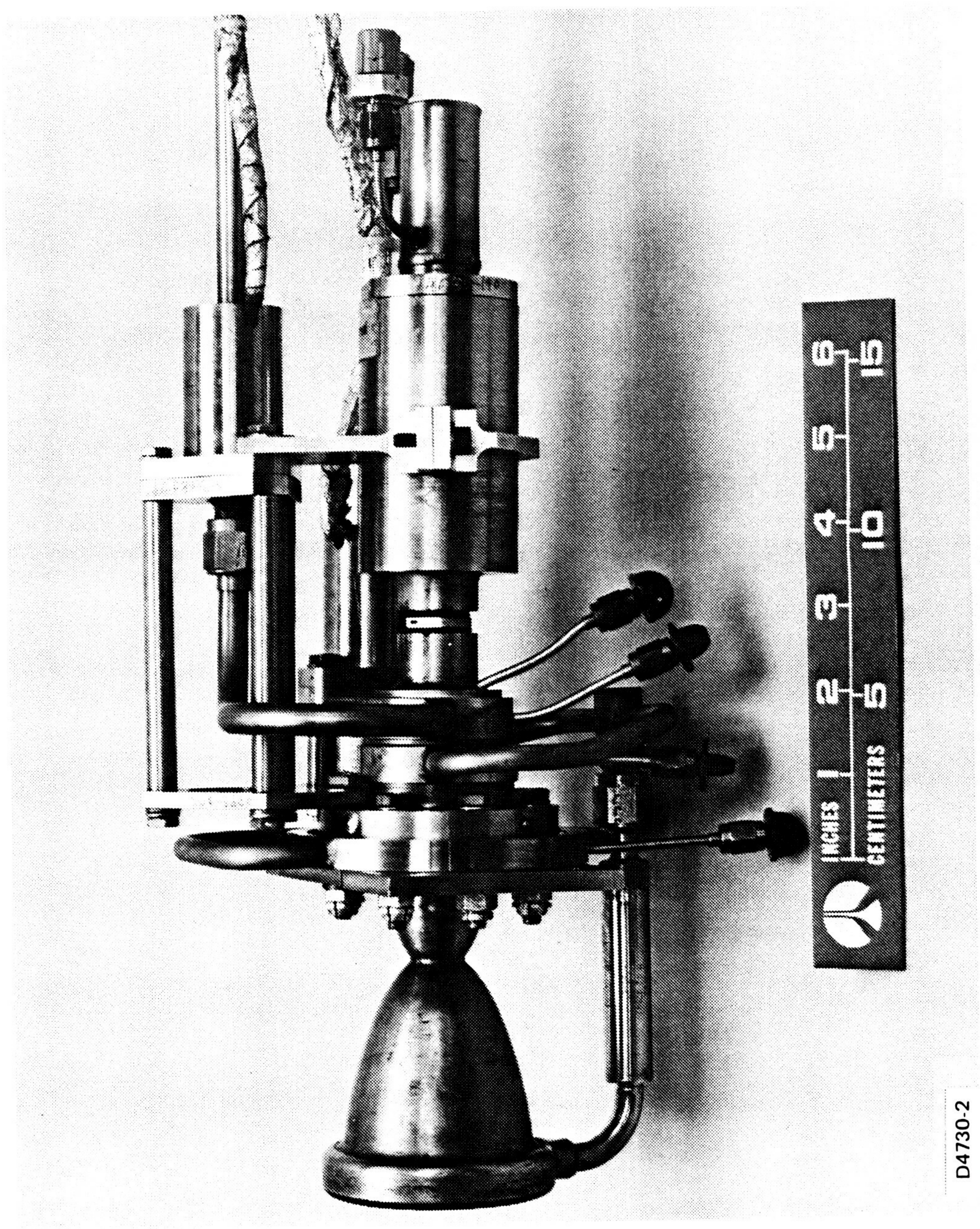
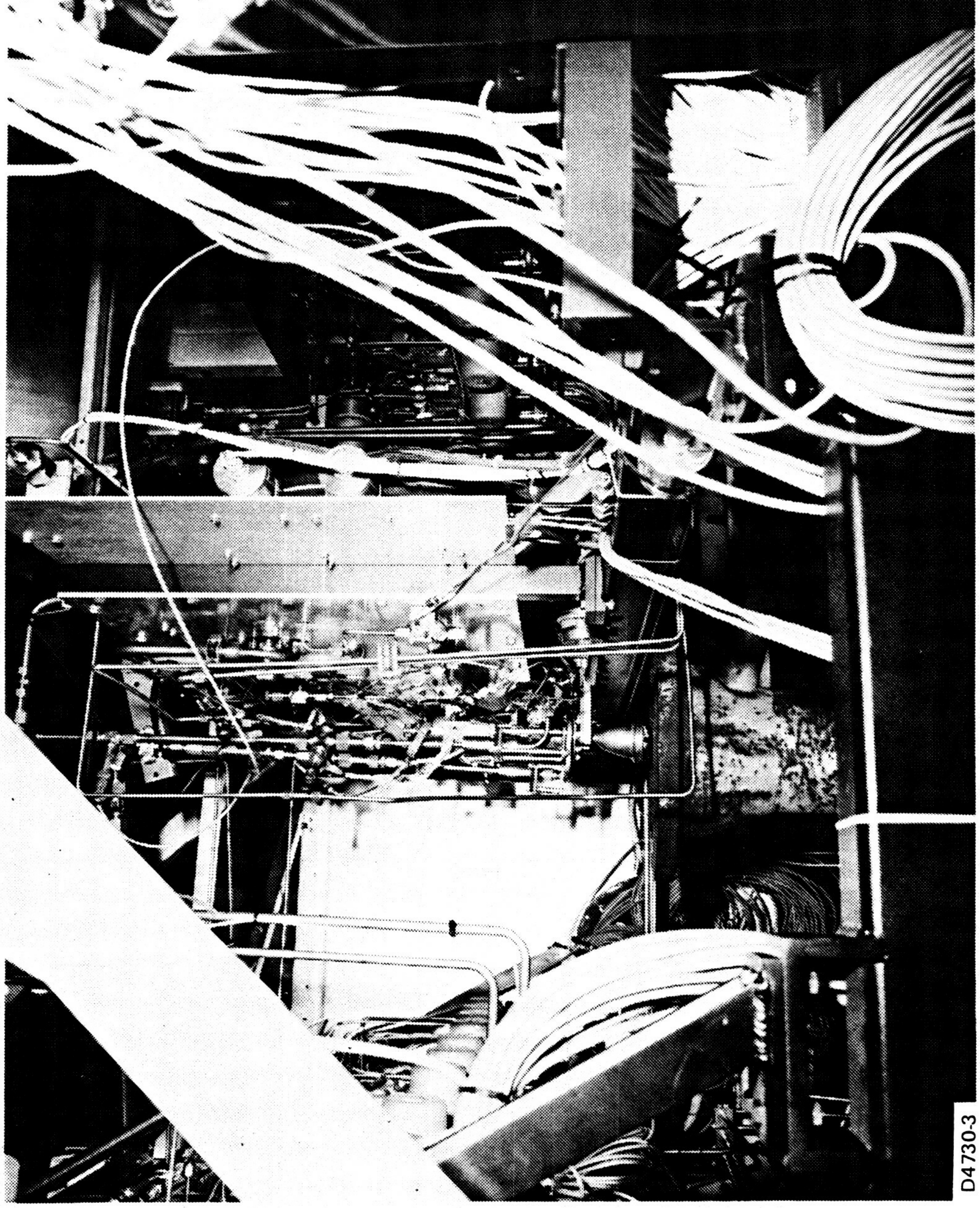



Figure 12. Rocketdyne Prototype 8:1 Thruster

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY



D4730-3

Figure 13. Rocketdyne Prototype Thruster in Test Bed for Initial Testing

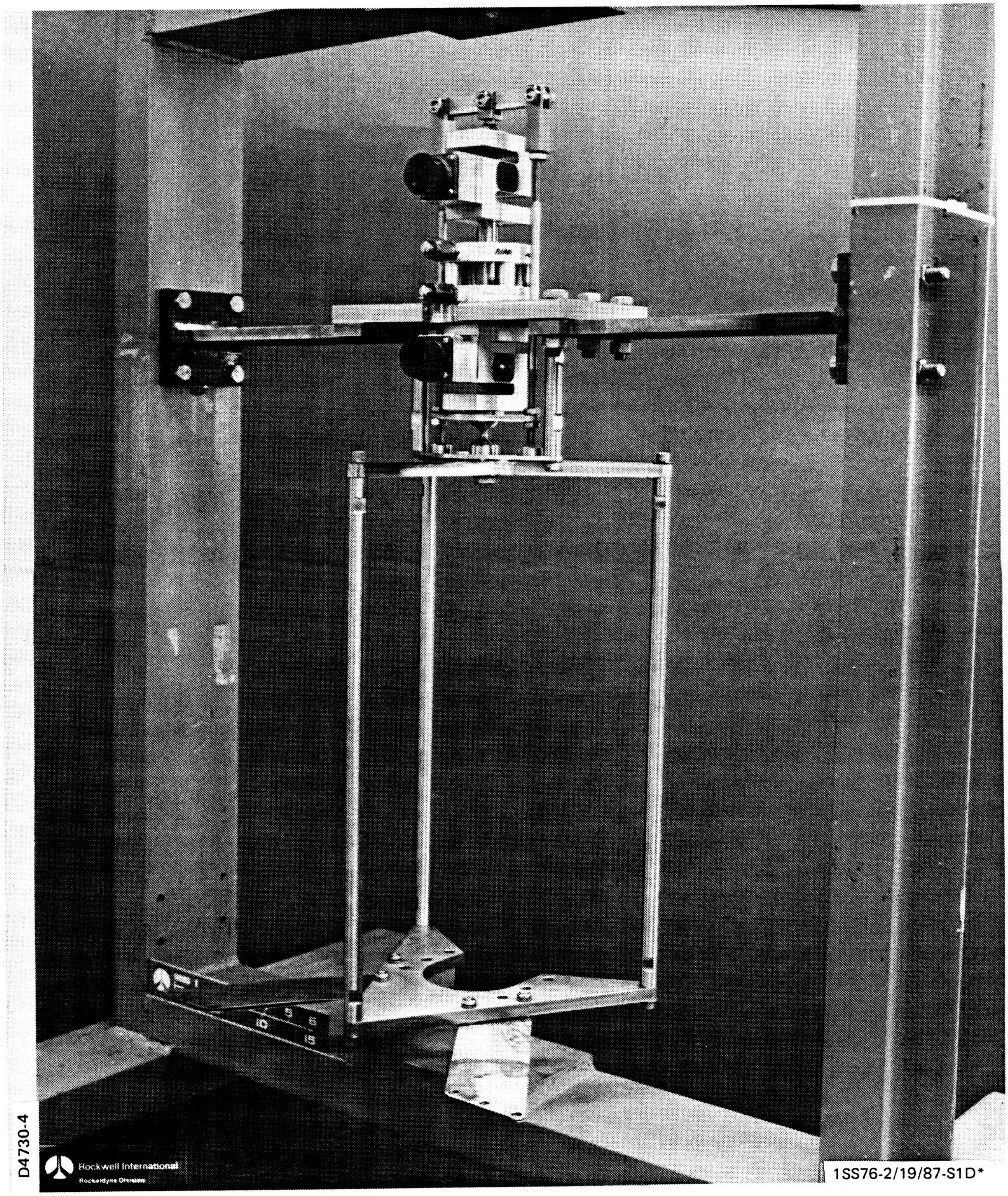



Figure 14. Thrust Measuring System Before Installation in Test Bed

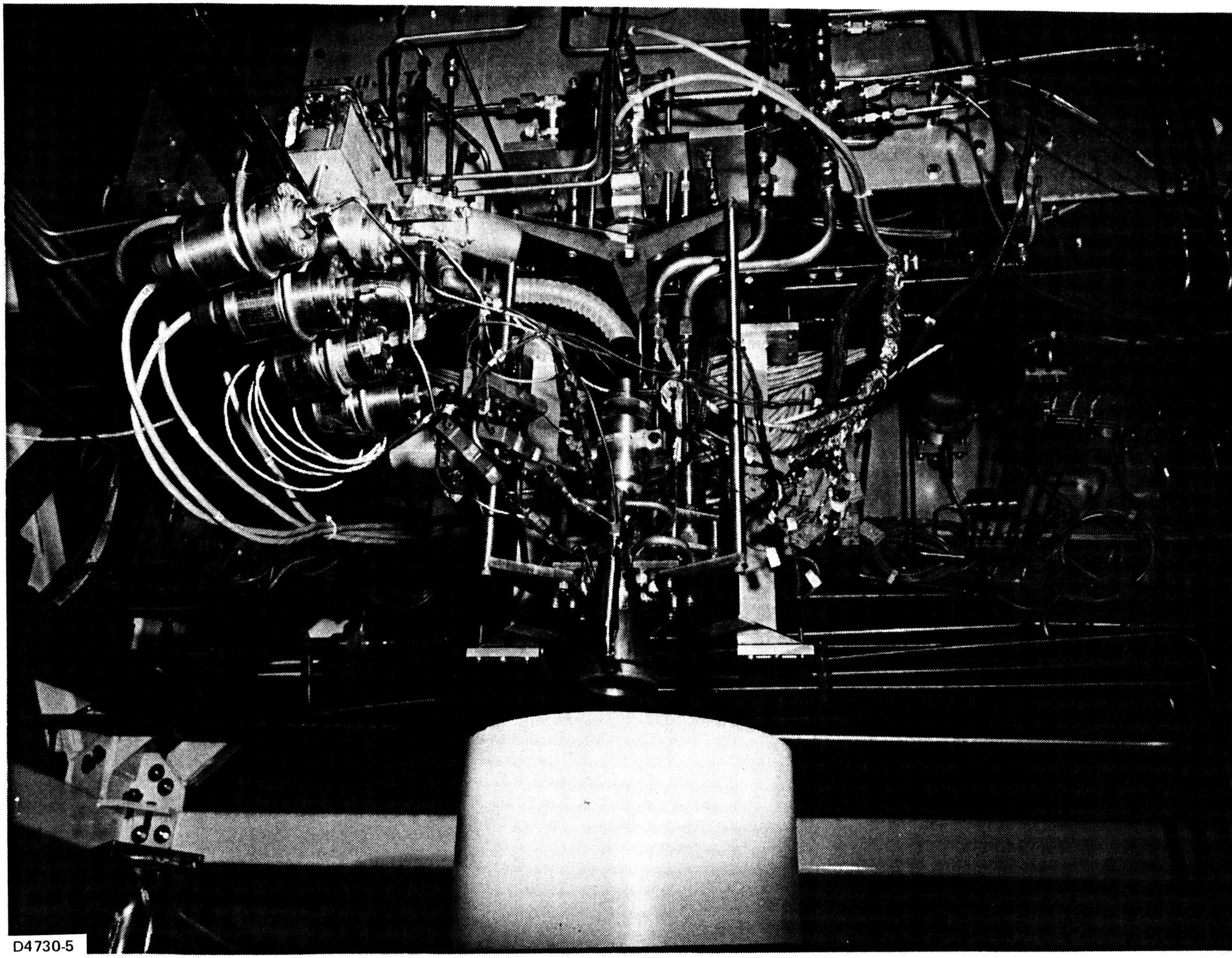



Figure 15. Rocketdyne Prototype Thruster in Thrust Measuring System for Checkout of System on Test Bed

With the addition of water electrolysis to the baseline system as the propellant supply, the need for an electrolysis system operation on the test bed became apparent. As a result, an electrolysis module was designed and fabricated at Rocketdyne to fit on top of the existing test bed cube. Components to be tested on the module include Arde-Steel tanks, SCI-wrapped tanks, a Life Systems Incorporated (LSI) electrolysis unit, and a Hamilton Standard (HSD) electrolysis unit.

The module also includes canisters to contain each of the water electrolysis units not currently operable in a vacuum. Molecular-sieve dryers designed by Boeing and fabricated at MSFC, are also included on the module. Fig. 16 shows the module assembly in the workshop before installation. In Fig. 17, an LSI technician is connecting the LSI 350-psig water electrolysis unit to the container ports. Fig. 18 and 19 show the installation of the module into the test facility.

Two major water electrolysis tests have been planned and are summarized in Table 3. The central objective of each test is demonstrating successful automated system operation. All test operations including electrolysis unit health monitoring, periodic dryer saturation and regeneration, and system control functions are fully automated. Manual overrides provide flexibility during test to allow variable dryer regeneration cycles. During a nominal test, however, minimal or no human support is required.

All tests have nearly identical test sequences. The first operation performed is the initial primary dryer bakeout. During this operation, the primary dryers are heated to 450°F and exposed to vacuum. Subsequently, the vacuum and heat are removed and a short cooldown period to 120°F is initiated. When both primary oxygen and fuel dryers are stable at 120°F, the initial primary dryer bakeout is complete.

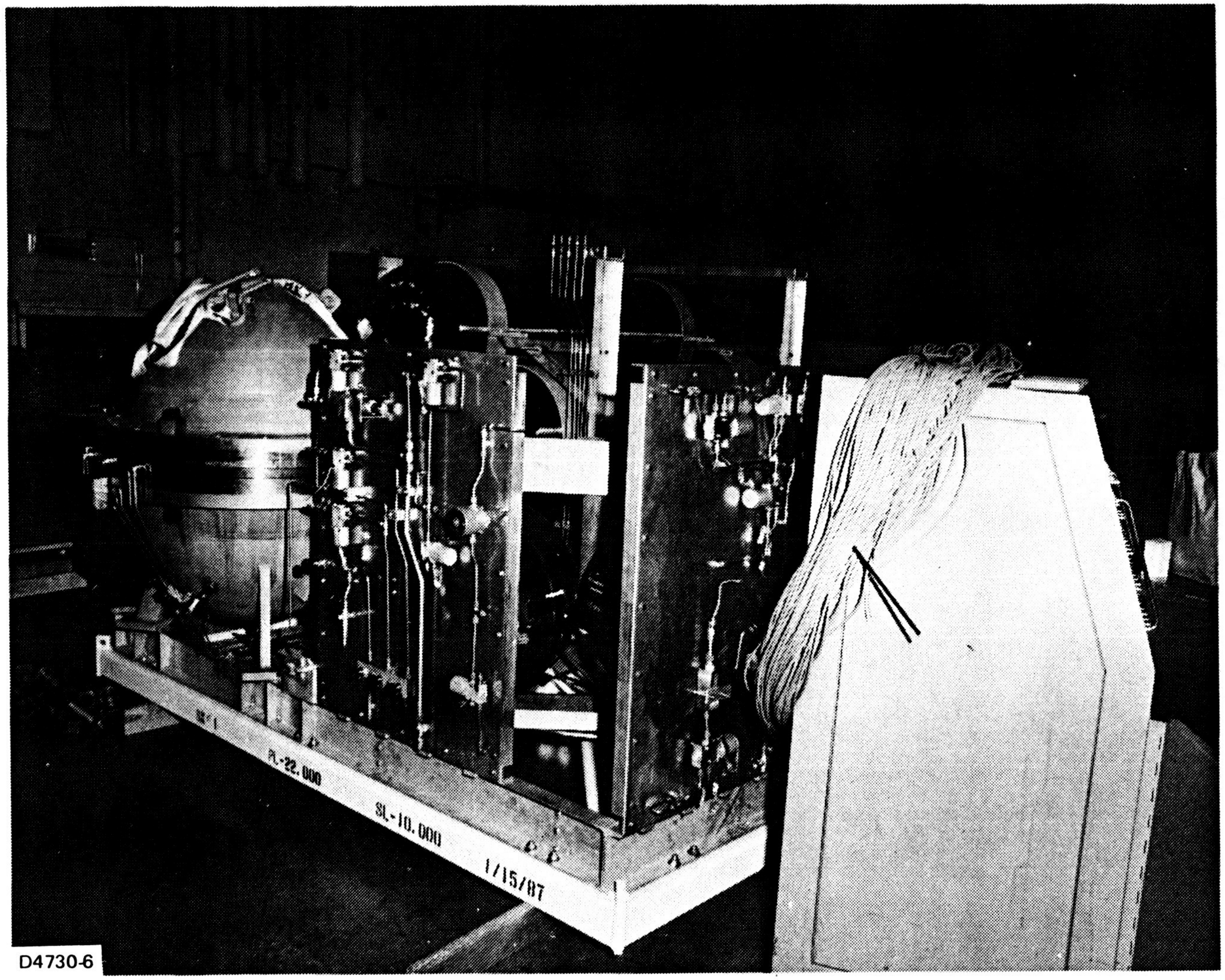



Figure 16. Water Electrolysis Module in MSFC Workshop

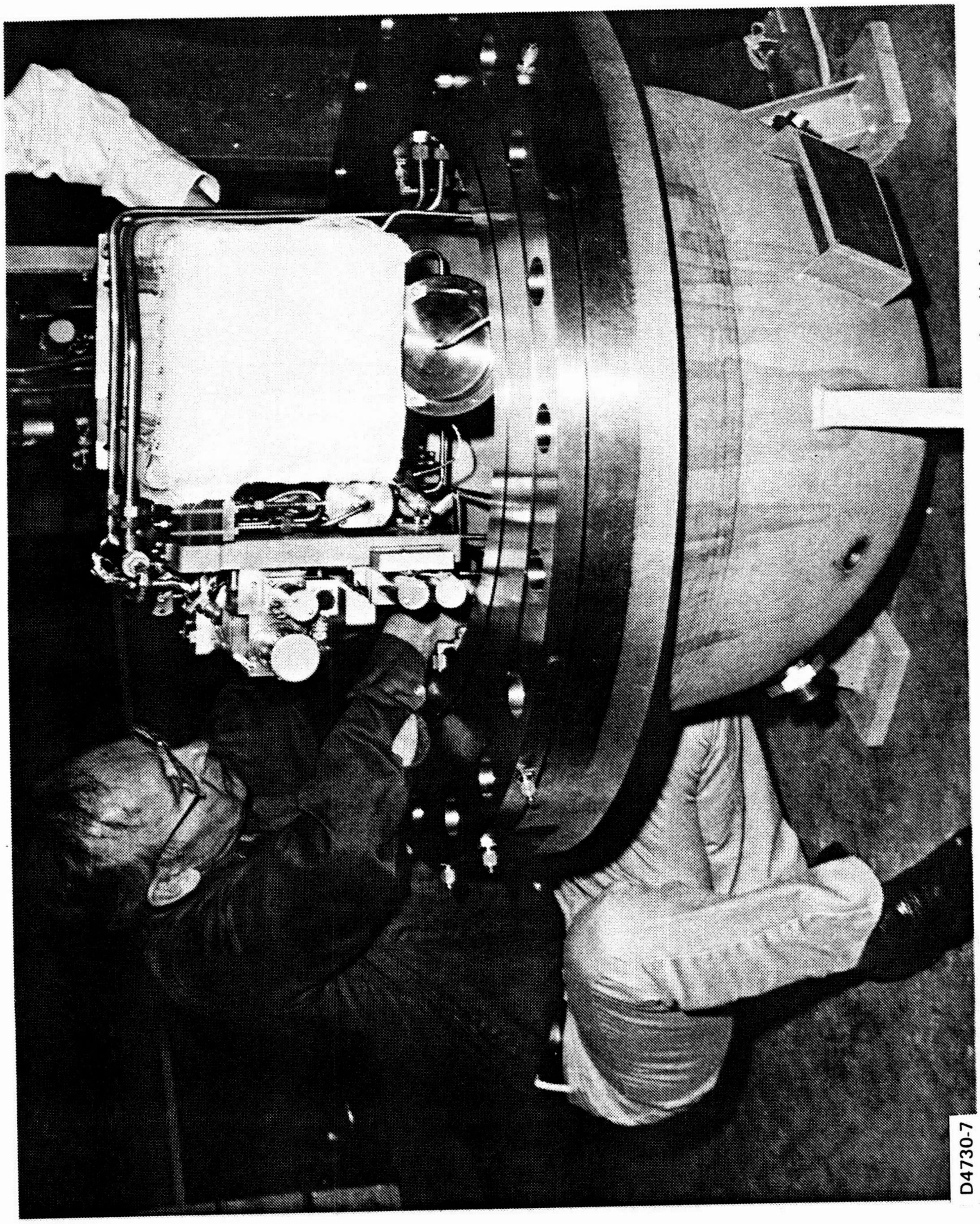
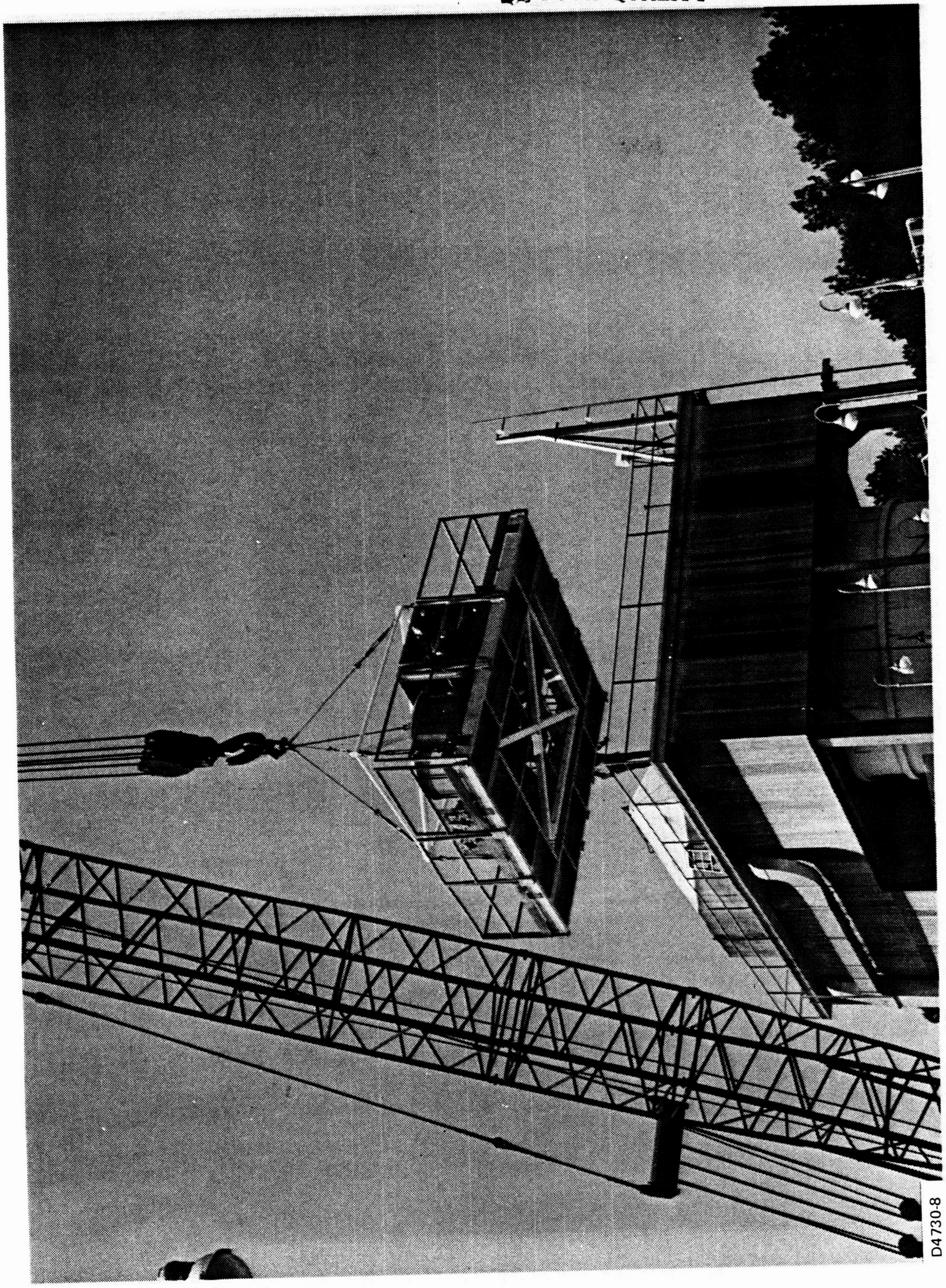



Figure 17. LSI Technician Connecting Electrolysis Unit to Pressure Container Pass Throughs

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY



D4730-8

Figure 18. Installation of Water
Electrolysis Module into Stand

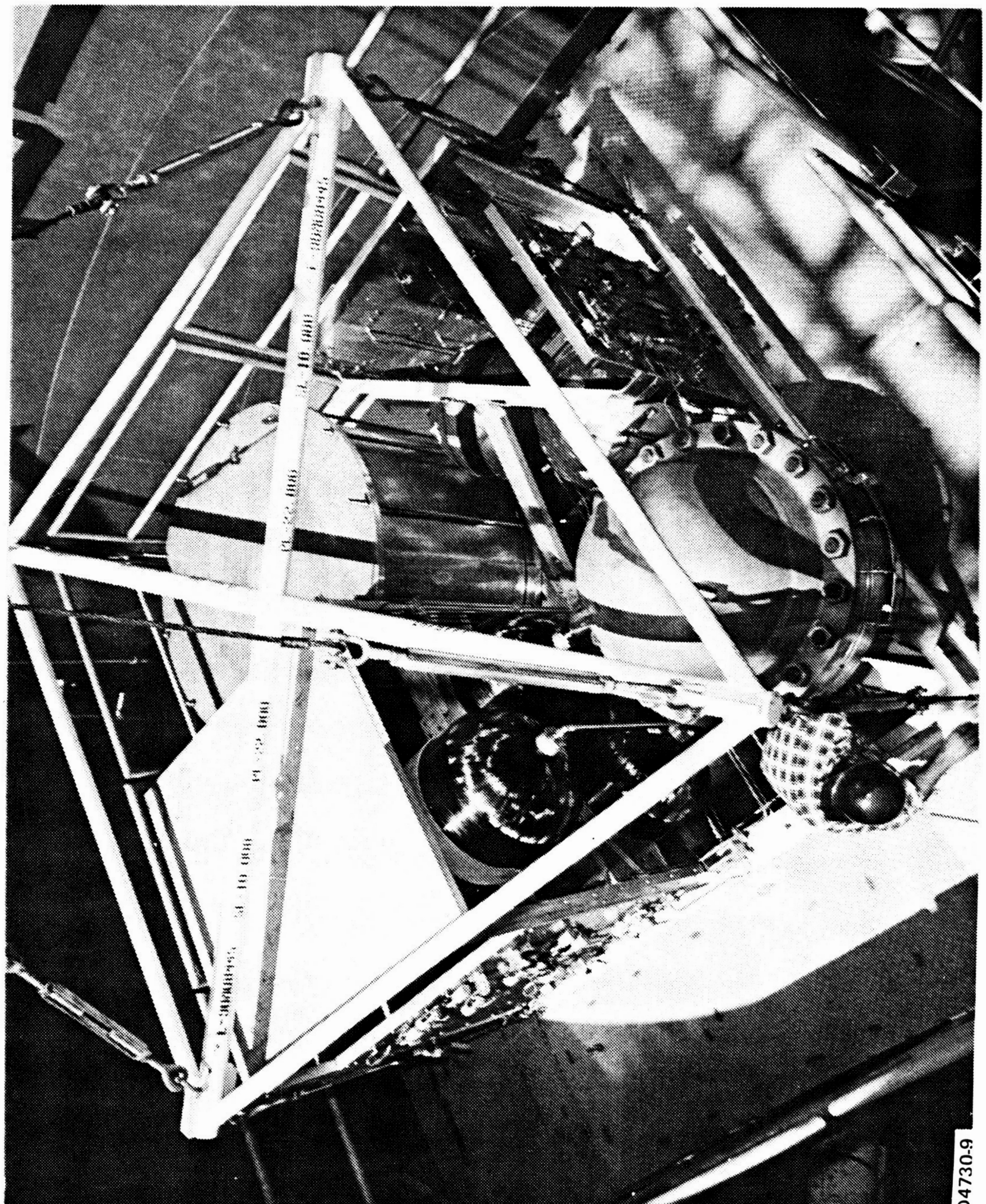



Figure 19. Water Electrolysis Module Installed on Top of Accumulator Module in Stand

ORIGINAL PAGE IS
OF POOR QUALITY

Table 3. Electrolysis Test Plans (Three Primary Test Series are Planned on Electrolysis Systems)

| Test | Objectives | Duration (days) |
|---|---|---|
| 1. LSI 350 psia | Demonstrate electrolysis, dryer operations, thruster hot fire | 5 |
| 2. HSD 1000 psia | Demonstrate electrolysis, dryer operations, thruster hot fire | 15 |

Electrolysis operation is initiated by a system command to the electrolysis unit controller. Following an electrolysis transition period, $O_2$ and $H_2$ gas are generated. Table 4 shows the steady-state flow rates for the LSI 350-psia and HSD 1000-psia systems. The hydrogen dryer saturates approximately twice as fast as the oxygen dryer (5.58 hours versus 11.17 hours). As a result of their higher saturation rate, the hydrogen dryers pace the primary and secondary dryer switching sequence. For example, during the LSI 350-psia test, the secondary dryer will alternate with the primary dryers into the system in 6-hour increments during test. During the 6 hours that the secondary dryers are being saturated, the primary dryers will be exposed to 450°F and vacuum as previously described. The primary and secondary dryers will be alternated into the system throughout test until the accumulators reach the electrolysis operating pressure, either 350 psia or 1000 psia. At this point, the electrolysis units are powered down, the accumulators locked off, and the manifolds vented. Following cell pumpdown, a thruster test will subsequently be performed utilizing the electrolysis-generated $O_2$ and $H_2$. Residual propellant may be stored or vented.

Data acquisition during test is totally automated. All control parameters except the electrolysis units will be recorded on the control system. The electrolysis units will be controlled via their own controllers which also monitor their parameters. The control system records data on hard disk for periodic dump to floppies during test or at the end of test. The LSI controller records on a PC floppy which is converted to an IBM format via a

Table 4. Summary of Dryer Saturation Performance as a Function of Product Gas Water Vapor Flow Rate

| | LSI Unit | | | | HSD Unit | | | |
|---|---|---|---|---|---|---|---|---|
| Product Gas | Min. Flow (pph) | Time (hr) | Design Flow (pph) | Time (hr) | Max. Flow (pph) | Time (hr) | Max. Flow (pph) | Time (hr/ days) |
| Oxygen | 0.0001 | 20.1 | 0.0018 | 11.17 | 0.0029 | 6.93 | 0.00015 | 160.8/ 6.7 |
| Hydrogen | 0.0019 | 10.6 | 0.0036 | 5.58 | 0.0057 | 3.53 | 0.00031 | 77.8/ 3.24 |

NOTE:

1. LSI unit operating at 350 psia and 130°F.
2. HSD unit operating at 1000 psia and 120°F.
3. Dryer saturation time = lb of absorbed water/100-lb MOL SIEVE + quantity of MOL SIEVE/moisture flow rate where lb of absorbed water/100-lb MOL SIEVE = 0.15 (LSI), 0.018 (HSD)

   Quantity of MOL SIEVE = 1.34 lb

   Moisture flow rate = function of operating point and product gas output.

proprietary disk. The frequency of disk changes is governed primarily by the controller sample rates. The HSD controller will line print and record on floppy disk via an IBM AT.

Every 24-hour period, composite plots of the test bed data will be generated. Currently, 18 composite plots are required to summarize system performance for a 24-hour period. Following test, the data will be reprocessed and merged into a set of summary composite plots covering the entire test duration. Real-time displays for the LSI/HSD and control system channels as well as facility data are provided for easy viewing.

Chemical analysis of the $O_2$ product and the $H_2$ product will be accomplished by sampling downstream of the dryer. Samples will be taken every 12 hours. The primary task of the chemical analysis is to detect mixed products (i.e., $O_2$ in $H_2$ stream or $H_2$ in $O_2$ stream). Mixtures indicate a possible electrolysis deficiency in barrier effectiveness resulting in less efficient operation. Of secondary importance is the detection of elements potentially detrimental to storage tanks (i.e., chlorine). Mixed products are not expected to pose a safety threat since the $O_2$ and $H_2$ concentrations are expected to be 0.5% or less.

Operating procedures are nearly identical for all systems. Performance measurement and success criteria are also similar. The primary success criteria beyond meeting nominal operating criteria is measuring specific energy. Specific energy is equal to kW•h consumed/LBM $H_2O$ electrolyzed. Specific energy is the most important measure of electrolysis efficiency and has a major impact on the entire system configuration (i.e., accumulator size, energy budget, and operational requirements).

The electrolysis system testing began in early July 1987 with a complete LSI 350 psi electrolysis system checkout test including operation of the dryers. The LSI 350 psig electrolysis system test was begun in late July. The test proceeded for 3 days until system pressures dropped sharply indicating leakage in the $GH_2$ system. Subsequent checks revealed KOH in the lines upstream of the dryer due to a malfunction in the electrolysis unit apparently caused by earlier erroneous pressures applied to purge ports. The KOH had attacked components in the system plumbing causing leakage.

The test was considered a qualified success in that gas was produced and delivered to the storage tanks up to 160 psig under automatic control prior to the malfunction.

The LSI unit was removed and retained for repairs and is scheduled for retest following the Hamilton Standard 1000 psig unit test.